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Energy retrofit of a single-family house: Life cycle net energy saving and environmental benefits

Marco Beccali [a], Maurizio Cellura [a], Mario Fontana [a], Sonia Longo [a], Marina Mistretta [b,*]

[a] Dipartimento di Energia, Ingegneria dell'Informazione e Modelli Matematici—Università di Palermo, Viale delle Scienze Ed. 9, 90128 Palermo, Italy
[b] Dipartimento Patrimonio, Architettura, Urbanistica—Università Mediterranea di Reggio Calabria, Salita Melissari, 89124 Reggio Calabria, Italy

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A B S T R A C T

When a building undergoes a retrofit project, the goal of assessing energy and environmental performances of retrofit actions is a complex matter. Building and its environment are complex systems in which all sub-systems are strongly interdependent and influence the overall efficiency performance. In the following paper, starting from a literature review of building life-cycle studies, the authors highlight that there is a strong interplay among all the phases of a building life-cycle, as each one can affect one or more of the others.

In detail, starting from the results of a “cradle to grave” life cycle study of an existing Mediterranean single-family house, a set of retrofit actions voted to reduce the energy consumption during the operation is analysed. The proposed actions are addressed to improve the thermal performance of the building envelope and the energy efficiency of technical equipment. Performance assessment of these actions has been carried out not only considering the related effects on energy saving for building operation, but also taking into account other phases of the life cycles. In fact, these measures will cause an increase in the building embodied energy, which is the energy embedded in building materials, utilised in transportation and construction processes, in maintenance and demolition. Thus, a balance between the energy saving during operation and the avoided environmental benefits due to the other phases has been done. In particular, the embodied energy and the environmental impacts related to production, transportation and installation phases of the required material/components for retrofit implementation are assessed. In other terms, LCA allows to estimate the reduction of the operation energy and the increase of the embodied energy within the building life-cycle, and to understand whether the achieved energy benefits could be supported in a life cycle perspective or were overcome by the environmental burdens of the actions.

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* Corresponding author. Tel.: +39 0965 385210.
E-mail address: marina.mistretta@unirc.it (M. Mistretta).

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1. Introduction

1.1. Background

In Europe many policy tools have been adopted to increase the energy efficiency of the existing building stock, as part of the plan aimed to reach a low carbon economy. In such a path the most important legislative tool in the European Union (EU) is the Directive 2002/91/EC on the Energy Performance of Buildings (EPBD) [1], which promotes the required measures to increase the energy performance of the buildings for all the EU Member States and introduces environmental performances as the most relevant driving force for energy saving in buildings (climate change, resource depletion, toxicity, etc.). Moreover the EU Directive 2006/32/EC encourages energy efficiency by means of the development of the energy service market and the delivery of energy efficiency strategies and measures addressed to end users [2]. The Directive 2010/31/EC (EPBD recast) strengthens the energy performance requirements promoted in [1] and clarifies some of its provisions to reduce the large differences among the Member States' practices [3]. According to the EPBD recast, all new buildings should be built as nearly zero energy buildings within 2020. Furthermore, a particular highlight is addressed to the retrofit of existing buildings. In fact, the EPBD recast prescribes that suitable measures should be taken by the EU Member States to decrease the energy demand of the existing buildings through retrofit actions addressed toward the target of nearly zero energy buildings.

Actually this aspect is a key issue for effective long and medium term energy and environmental policies, due to the following topics of the building sector:

- The turn-over rate of buildings is quite low and does not exceed more than 3% yearly [4].
- Buildings, including residential and commercial buildings, are the largest consumers of energy: they account for about 40% of the total EU's total final energy consumption and generate more than 30% of its emissions [5–7].
- Environmental performances (climate change, resource depletion, toxicity, etc.) are the most relevant driving forces for energy saving in buildings.

The goal of undertaking the energy and environmental assessment of building retrofit actions is a complex matter. The energy use during the building operation is a function of several factors, such as climate, building envelope and other characteristics, building occupancy and use, and heating and air conditioning equipment type and schedule [8–10]. When a building undergoes a retrofit project, the quantification of the related energy savings should include the following steps: (1) the assessment of the energy consumption due to the technical equipment; (2) the study how this energy consumption is related to significant variables such as climate, building occupancy, operation hours, etc.; (3) the assessment of the energy consumption due to the technical equipment after retrofit, through post-retrofit monitoring or building energy simulations and (4) the calculation of achieved energy savings through a balance between the post-retrofit energy uses and the pre-retrofit ones.

This approach is limited to the assessment of operation energy balances and is not capable to deal with global energy and environmental benefits related to the designed retrofit. However, buildings require energy over their lifespan; thus an exhaustive assessment of the environmental impacts may not neglect energy consumption, exploitation of natural resources and pollutant emissions in a life-cycle perspective. The improvement of energy performances in building operation still must be the primary goal of the design step to reduce the operating energy demand, improving the thermal insulation of the building envelope and the efficiency of energy devices, installing alternative energy using systems and renewable energy technologies for heating, domestic hot water and electricity generation [11,12]. Nevertheless, such measures could lead to an increase in embodied energy of buildings, which is embedded in building materials, transportation and construction processes, and in the energy needed for demolition (disposal/recycling) [13,14].There is a strict interplay among all the phases of a building life-cycle, as each one can affect one or more of the others, highlighting the relevance of the life-cycle approach to perform a reliable and complete building energy and environmental assessment [15].

1.2. Literature review

When the energy use of a building is discussed from a lifecycle perspective, energy use in building operation accounts for 70–90% of energy used during its life cycle. There are a number of literature life-cycle studies with results supporting this concept [15–24]. Some of the life-cycle assessments carried out on low-energy houses focused on minimising the final energy use or the purchased energy in the operation phase, while the energy consumption in other phases is often neglected [17–19].

All of the cited studies differ with regard to calculation methodology used to account for the total energy use, for climate, country, type of building, type of construction, assumptions on indoor climate and source of data (whether measured or calculated). However they reach similar conclusions which support the statement above. The consequence is that moving toward low-energy building and to Net ZEBs the relative share of energy use related to building operation will decrease.

An interesting Swiss study, based on a life cycle approach, estimated that the construction sector is responsible for about 50% of the life-cycle primary energy consumption in Switzerland [18]. Such a consumption is mostly due the single-family dwellings, followed by the multi-family dwellings. The highest contributions are given by the energy use for heating and hot water supply (50–70% of the global consumption), while embodied energy of the building materials accounts for 10–20%.

Another life-cycle study was carried out within the EU Building Project “Environmental Improvement Potentials of Residential Buildings”. It assessed the environmental improvement potentials of residential buildings, including all relevant types of existing and new buildings used as household dwellings in the EU-25 [22]. Such a study took into account the residential building stock in the EU 25, divided in single-family houses, multi-family houses, and high-rise buildings. The operation and the end-of-life phases were included in the existing building analyses and the construction phase was added in the new ones. The results showed a common trend both for new buildings and existing buildings: the high-rise

buildings involved the lowest life-cycle impacts, while, on average, single-family houses have the highest impacts (i.e. a primary energy requirement of 1000–1500 MJ/(m^2 year), and a Global Warming Potential (GWP) of about 70–80 $kgCO_{2eq}$/(m^2 year). Such a trend depends on the effects of the climatic conditions, the building shape and the shell insulation on the internal thermal loads. For new buildings, the use phase dominates the total environmental impacts at EU level, but the construction phase also accounts for a large rate of the impacts (8.3–34.3% of the environmental impacts).

Another interesting comparative study among different residential buildings was presented in [23]. Sixth semi-detached house typologies, common in the central Europe, with a living surface area from 176 m^2 to 185 m^2 and an average useful life of 80 years, were analysed. The houses differed in their energy efficiency of the heating system as well as in building materials. The reference house had an energy demand for heating of 353 MJ/(m^2 year). The other houses showed values of energy consumption between 122 and 187 MJ/(m^2 year), which characterize low energy houses. The houses only differed slightly in their sizes and layouts. The study showed that the adoption of high efficiency design solutions (higher insulation, high efficiency plants, low energy materials, etc.) sensibly decreased the global energy demands with respect to a common reference building. Worse performances of the examined buildings were generally to be related to inadequate insulation or to the use of electricity for the building heating.

An Italian case study compared a standard house and a low energy house, clearly showing the changing role of embodied energy in relative terms [24]. The primary energy use for construction and maintenance increased by 20% when taking the step from the standard house to a low energy house. However, the relative share of embodied energy of the total life-cycle energy consumption increased from 17% to roughly 50%.

All the above case study shows that the embodied energy has decreased slightly over time, indicating that the construction of buildings and technical systems in general has become more effective over time. However, the relative share of embodied energy in the life-cycle energy assessment is increasing and the most relevant efforts that could be made in the future will be to choose insulation material with low embodied energy instead of increasing the amount of insulation, and to increase the share of renewable energy use.

The above case studies show different outcomes. Thus it is not appropriate to directly compare the cases with each other. However, they are useful to remark that the above case studies differ for climate, country, type of building, type of construction, methodological assumptions on data quality and system boundaries, and not less important the user behaviour, which affects the energy consumption in each end-uses.

1.3. The role of the Life Cycle Assessment (LCA)

The relevance of considering environmental-related product information by Life Cycle Assessment (LCA) is broadly recognised. It represents a suitable methodology to estimate the eco-profile of a building, including all the phases in which built structures and facilities are procured and erected (manufacturing and transportation of the construction materials and components to the building site), operation, maintenance, renovation, the disassembly and the waste management [25,26].

In building and energy analyses LCA allows for [27,28]

- the integration of the building environmental performance targets into the certification programmes and policies by the authorities, which traditionally are mainly focused on energy use as electricity and fossil fuels in building operation do not encompass the other relevant life-cycle phases;
- the advice for designers and consultants to fulfil the above targets in early design and in retrofit projects, by choosing among different design options; and
- the assessment of the most effective actions addressed to save energy and to minimize environmental impacts along the whole building life-cycle.

Nevertheless a LCA of a building is a complex task due to several factors like the long lifespan (often more than 50 years), the number of involved stakeholders and the singularity of each building. Besides, during its life a building may undergo significant changes in its shape, technical equipment, and/or function, involving significant changes in the environmental burdens. When the energy performances of a building increase by means of retrofit measures, additional materials and components are applied, resulting in a higher embodied energy [29]. Thus, it is useful to assess the life-cycle environmental impacts and the embodied energy of the retrofit measures, and the post-retrofit building energy consumption. In this case, proper design and material/component selection of the retrofit actions are critical to minimize the related environmental impacts.

In the following paper, starting from the results of a “cradle to grave” life cycle study of a conventional existing building [30], a set of energy retrofit actions is planned to increase the energy efficiency of the original building. Then a life-cycle approach is applied to undertake the related eco-profiles. Thus, a balance between energy saving and environmental benefits and drawbacks concerning the assessed retrofit actions is carried out. In detail, the presented study has the following aims:

(1) to calculate the life-cycle energy and the environmental impacts arisen from the production, transportation and instal-

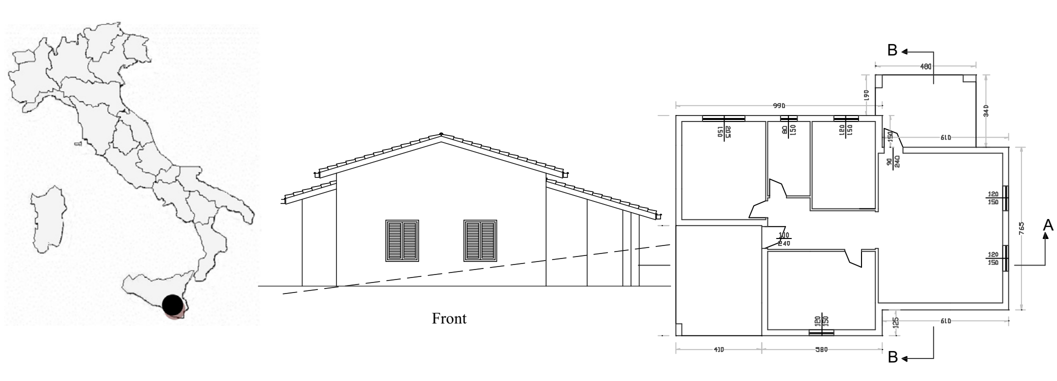


Fig. 1. Geographic position and dimensional drawings of the building.

lation phases of the retrofit measures, and to quantify the involved influence on the building eco-profile;
(2) to evaluate whether the achieved post-retrofit benefits in terms of energy saving could be confirmed from a life cycle perspective or are overcome by the broader environmental impacts. To this aim, payback indices were added to the set of life-cycle impact indicators;
(3) to point out the changes in relative relevance of operating and embodied energy in the building's life cycle.

2. Description of the existing building

The assessed building is a Mediterranean single-family house, located in Palermo in Southern Italy, 270 m above sea level, currently used by three occupants. It was built on one level with a heated area of 110 m^2 (Fig. 1). The local climate has hot and wet summers, which affect significantly the energy demand for the building winter heating. Table 1 summarizes the main geographic and climatic data and some characteristics of the dwelling.

The structural frame is made of reinforced concrete with masonry block walls. The external walls construction include 20 cm bricks with a 9 cm of cavity filled with foam vermiculite. The floor is 20 cm thick, including perforated bricks and prefabricated reinforced concrete rafters. The roof has a wooden structure with composite materials and clay roof tiles cover. The ground floor lays on a structure made of reinforced concrete and cave crushed stones.

The external walls have a U-value of 0.96 W/m^2 K. The roof and the ground floor have a U-value of 0.60 W/m^2 K and 1.6 W/m^2 K, respectively. With regard to the transparent surfaces, the building is only equipped with wooden frame and double-glazing windows (U=2.8 W/m^2 K).

Heating and domestic hot water (DHW) are provided by a LPG (Liquefied Petroleum Gas) boiler. The heating system is equipped with steel radiators with insulated steel pipes for distribution. Summer air cooling is provided with reversible electrical heat pumps with an average seasonal energy efficient ratio of 3.3 in cooling mode.

2.1. LCA of the existing building. Main results

The LCA methodology was applied to the above described building in compliance with the international standards of the ISO 14040 series, including the steps of material and component production, building erection, operation, maintenance and end-of-life [31]. The eco-profile of the existing building is showed in Table 2.

The selected functional unit for the LCA study was the assessed building. The life-cycle primary energy was calculated according to the Cumulative Energy Demand (CED) Method [32]. Embodied energy was estimated as the energy content, valued as primary energy, of the building materials and technical components, including the raw material acquisition, manufacturing and the production of materials and technical components, and the transportation to the building site. It represents the 26% of the CED (1217 GJ). Demolition energy, that is the primary energy consumption in the dismantling and waste disposal at the building end-of-life, accounted only for 2% (101 GJ). The operation step accounts for the highest contribution, about 72% on CED (3327 GJ). Considering 50 years of lifespan for the building, the operating energy was estimated as the primary energy consumption for end-uses such as heating, cooling, domestic hot water (DHW), lighting, electric devices, and cooking (Fig. 2). A 3-year monitoring of the building end-uses was carried out to estimate electricity use for household appliances and cooling, LPG consumption for winter heating, DHW and cooking. Table 3 shows the primary energy consumption related to the different end-uses during the building operation. From the monitoring outcomes energy consumption for the thermal uses accounted for about 40%, while electricity use accounted for about 60%.

On the basis of the monitoring outcomes, a 1-year transient simulation of the assessed building was carried out through TRNSYS software in order to assess the heating and cooling energy loads [33]. The model was developed to describe the thermal energy performance of the building envelope. Weather data, thermal, mass and size features of envelope, and thermal internal gains worked as inputs for the model (Fig. 3).

The modelled energy demand for winter heating revealed that the thermal performances of the existing building do not to comply with the Italian laws on buildings' energy performance [34]. Therefore the following considerations can be made:

- the components of the building envelope need an improvement of thermal properties to match the national legislative values and
- the most significant contribution to the operation energy is given by the electricity consumption for electrical devices.

On the basis of the above considerations, the following sets of retrofit actions were proposed to reduce the energy consumption during the building operation:

Table 1
Characteristics of the assessed building.

Geographical and climate data		Building features	
Latitude	38°09′ N	Total floor area	110 m^2
Longitude	13°18′ E	Heated area	110 m^2
Altitude	270 m.a.s.l.	External wall area (S)	411 m^2
Degree days	751	Gross volume (V)	402 m^3
Climatic area	B	Shape factor (S/V)	1.02 m^2/m^3
Low heating period	121 days		

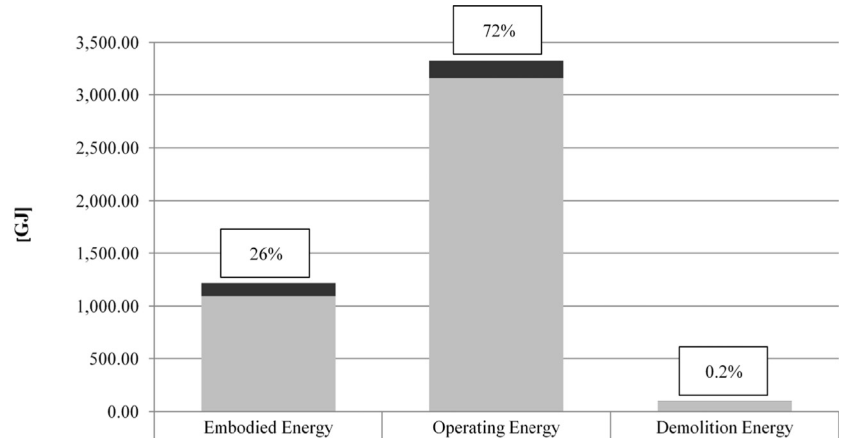
Table 2
Eco-profile of the existing building.

Indicator	Unit	
Cumulative Energy Demand (CED)	GJ	4645
Global Warming Potential (GWP)	$kgCO_{2eq}$	324,270
Ozone Depletion Potential (ODP)	$kgCFC_{11eq}$	0.05
Acidification Potential (AP)	$kgSO_{2eq}$	1193
Eutrophication Potential (EP)	$kgPO_{4eq}^{3-}$	270
Photochemical Ozone Creation Potential (POCP)	kgC_2H_{4eq}	378

Table 3
Primary energy consumption for building end uses before retrofit.

End uses	Lifespan consumption (GJ)	Specific consumption (GJ/m^{2}y)
Heating[a]	533.5	0.10
Cooling	148.9	0.03
DHW	436.0	0.08
Cooking	133.4	0.02
Electric appliances	1978.0	0.36
Other uses	98.0	0.02
Total	3327.8	0.61

[a] It also includes the energy consumption related to the LPG transport.



	Embodied Energy	Operating Energy	Demolition Energy
■ Renewable (GJ)	123.23	169.71	1.42
■ Non Renewable (GJ)	1,094.19	3,157.41	99.20

Fig. 2. Contribution of the embodied energy, the operating energy and the demolition energy to the life-cycle primary energy consumption.

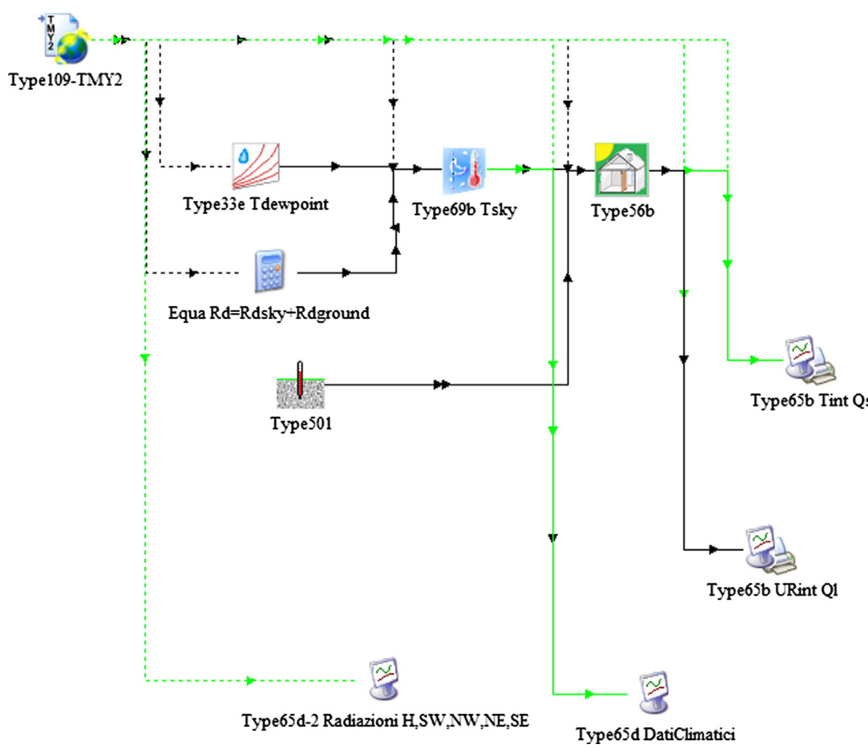


Fig. 3. Building TRNSYS model.

(1) thermal insulation of the building envelope in order to reduce thermal loads;
(2) replacement of the existing boiler with a high-efficient boiler in order to reduce the energy consumption for thermal uses (DHW generation and winter heating); and
(3) installation of a grid-connected photovoltaic plant in order to reduce the primary energy consumption for the electrical devices.

However, for the adoption of the above technical solution to reduce the operating energy demand, extra materials and components are required, resulting in higher embodied energy of the building. Then, the life-cycle approach in the energy and environmental assessment of the retrofit measures is necessary to avoid shifting environmental burdens from one step of the life-cycle to another.

3. Case study: retrofit actions on a Mediterranean single-family building

3.1. Goal and scope definition

According to the life cycle approach, the main goals of the study are

– to assess the energy and environmental impacts of the retrofit actions,

- to assess the net energy saving achievable by the proposed actions and the related embodied energy, and
- to evaluate the environmental benefits and drawbacks concerning the assessed retrofit actions to highlight whether the energy saving and the avoided environmental impacts offset the embodied energy of the retrofit actions and the related life-cycle environmental impacts.

Energy consumption in the building life-cycle is calculated as primary energy, which represents the most effective indicator to express consumption of energy under different forms. This calculation must take into account all the losses related to the processes of extraction of the resources, their transformation and distribution and requires the assessment of electricity and fossil fuel uses, according to different efficiencies in the final uses (heating, domestic hot water, lighting, etc.).

The life-cycle impact assessment (LCIA) is carried out by means of indicators and characterisation factors of the EPD scheme (Environmental Product Declaration—EPD) [35]. The Cumulative Energy Demand method is used to account for the overall primary energy requirement of the assessed actions [32].

3.2. Definition of the functional unit and system boundaries

According to the UNI EN ISO 14040 standard, the functional unit is defined as the reference unit through which the performance of a product system is quantified in a LCA [31]. Thus, in the examined case study each retrofit action proposed was selected as functional unit as follows (see Tables 4 and 5):

- Thermal insulation of the building façade (224 m^2) by means of EPS board (Expanded Polystyrene) coating, 12 cm thickness. With this measure U-value decreases from 0.96 to 0.27 W/(m^2 K).
- Thermal insulation of the roof (142 m^2) by means of rock wool boards, 8 cm thickness. With this measure U-value decreases from 0.60 to 0.25 W/(m^2 K).

Table 4
Changes in thermal performance of the envelope component.

Component	Before retrofit	Standard limit[a]	After retrofit
U value	W/(m^2 K)	W/(m^2 K)	W/(m^2 K)
Walls	0.96	0.41	0.27
Roof	0.60	0.32	0.25
Basement	1.6	0.46	0.39
Specific primary energy	kWh/(m^2 year)	kWh/(m^2 year)	kWh/(m^2 year)
Demand EPi	86.74	38.00	10.88

[a] Italian Legislative Decree, 2010 January 26, Disposizioni correttive ed integrative al decreto legislativo 19 agosto, 2005. Aggiornamento del decreto 11 marzo 2008 in materia di riqualificazione energetica degli edifici (*Pubblicato su G.U. n. 35 del 12/2/2010*).

Table 5
Main characteristics of the PV plant.

Number of panels	9
Nominal power	2.16 kWp
Panel area	16.1 m^2
Tilt	30°
Azimuth	0°
Specific energy production	1450 kWh/(kWp y)
Total electricity production	3131 kWhel/y

- Dismantling and renovation of the ground floor (142 m^2), adding a layer of XPS (Extruded Polystyrene), 8 cm thickness. With this measure U-value decreases from 1.60 to 0.39 W/(m^2 K).
- A 2.16 kWp PV grid connected plant to be installed on the building roof (Table 5).
- A condensing boiler for replacing the existing boiler, with an average efficiency $\eta = 0.92$.

No retrofit action for windows was assumed because the existing ones have a suitable thermal performance (U lower than 2.4 W/(m^2 K)).

With regard to the system boundary of the study, embodied energy and environmental impacts involved in the production step of the retrofit material/components and energy plants were

Table 6
Materials embodied in the retrofit actions.

Component	Materials	kg
Envelope		
Roof	Wood	817.92
	Rockwool	599.81
	Polyethylene	32.66
	Plasterboard	1675.60
	Steel	213.00
Walls	Concrete	2161.60
	Sand	5440.96
	EPS	591.36
	Glass fibre	34.72
	Polypropylene	44.80
	Lime	595.84
Basement	Concrete	308.00
	EPS	2640.00
	Sand	6160.00
	Steel	338.80
	Tiles	5060.00
Plants		
PV	Metals (Aluminium brass, copper, etc.)	43.90
	Glass	164.16
	Multi-Si	451.50
Boiler	Metals (Aluminium brass, copper, etc)	19.58
	Steel	115.00
	Polyethylene	0.90
	Rockwool	8.00

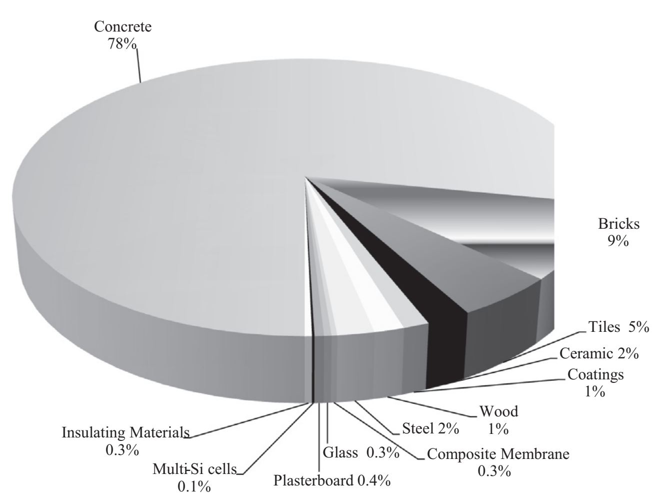


Fig. 4. Mass rates of embodied materials in the building after retrofit.

calculated, including the resource supply and manufacturing process. The contribution to the building eco-profile was calculated referring to the manufacturing process of the material/components and plants involved in the retrofit scenarios.

The end-of-life of the retrofit components was assessed as contribution to the end-of-life of the renovated building, after a life-span of 50 years. The energy for demolition, used to dismantle the building and to transport C & D wastes to landfill sites and/or recycling plants, was accounted for. Transportation at the building site and installation were neglected with regard to the production phase, since they were less than 1%. With regard to the use phase, the operating energy after retrofit was estimated.

A 50-year lifespan for the retrofit actions was assumed, except for the PV plant and the condensation boiler which were assumed to be replaced once during this time. With regard to these replacements the authors were not able to quantify any variation of performance for the new installations. This would involve considerations that go beyond the limits of the study.

The environmental impacts caused by the infrastructures were neglected. Therefore, the impacts of the construction of roads and the trucks used to carry the construction materials were not taken into account.

3.3. Data quality and Life Cycle Inventory (LCI) assumptions

According to the general framework provided by ISO 14040, the inventory analysis was carried out in order to quantify the environmentally relevant inputs and outputs of the studied system, by means of a mass and energy balance of each FU. To this aim, site-specific data were integrated with literature data. In particular, data related to the existing building were derived from [30]. Data about production of the retrofit components were provided by the producer companies in the sector. Inventory datasets on energy supply (electricity and fuels) and transportation were derived from [36]. LCI model was carried out by using the SimaPro software [32]. Fuel consumption and air emissions from transportation were calculated, depending on the transport mode and the distance between sites of production and the site of building construction.

Heating and cooling energy demand of the renovated building was derived from a 1-year transient simulation that was carried out through TRNSYS software [33].

The materials embedded in the building, when implementing the above energy retrofit measures, are summarised in Table 6, as they result from LCI. Fig. 4 shows the related rates, not including those materials representing less than 1% of the total mass.

3.4. Life Cycle Impact Assessment (LCIA)

LCIA was carried out in order to assess the energy and environmental impacts of the retrofit actions by means of suitable and meaningful indicators. The LCIA results were presented at the level of mid-point indicators.

In order to select relevant environmental indicators able to represent in a synthetic and comprehensive way the LCI results about the material and energy resource consumption and the environmental releases, the chosen impacts categories were referred to the main environmental indices and characterization factors included in the "Environmental Product Declaration" scheme.

In detail, life-cycle primary energy consumption is calculated according to the Cumulative Energy Demand Method. In particular the following mid-point indicators were selected, since they are widely known and applied by LCA experts, as recommended by ISO 14040:

- Cumulative Energy Demand (CED).
- Global Warming Potential (GWP).
- Ozone Depletion Potential (ODP).
- Acidification Potential (AP).
- Eutrophication Potential (EP).
- Photochemical Ozone Creation Potential (POCP).

Table 7
Life-cycle impact assessment of the proposed retrofit actions.

Indicator	
Cumulative Energy Demand (CED)	333 GJ
Global Warming Potential (GWP)	18,223 $kgCO_{2eq}$
Ozone Depletion Potential (ODP)	0.053 $kgCFC_{11eq}$
Acidification Potential (AP)	61 $kgSO_{2eq}$
Eutrophication Potential (EP)	14.5 $kgPO_{4eq}^{3-}$
Photochemical Ozone Creation Potential (POCP)	7 kgC_2H_{4eq}

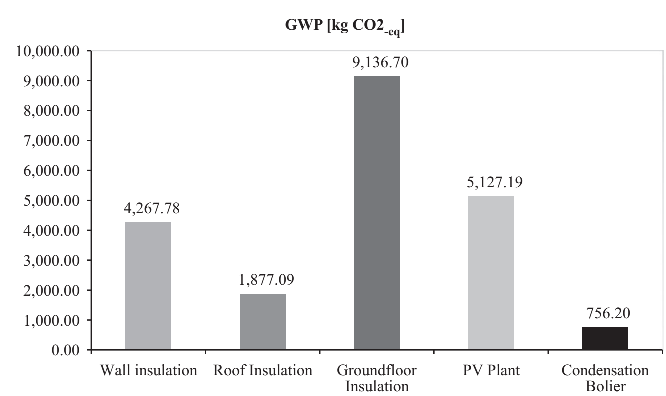


Fig. 5. Contribution of each retrofit actions to GWP.

Table 8
Contribution to the energy and environmental impacts of each retrofit measure.

Retrofit action	CED (GJ)	GWP ($kgCO_{2eq}$)	ODP ($kgCFC_{11eq}$)	AP ($kgSO_{2eq}$)	EP ($kgPO_{4eq}^{3-}$)	POCP (kgC_2H_{4eq})
Envelope						
Wall	69.77	4267.78	0.0003	16.62	1.57	0.62
Roof	38.03	1877.09	0.0005	11.61	1.31	0.80
Ground floor	110.67	9136.70	0.0510	20.83	1.98	1.04
Plants						
PV plants	49.07	2563.59	0.0011	10.40	8.01	4.23
Condensation boiler	6.84	378.10	3.01E−05	1.90	1.61	0.36

Table 9
Annualised net energy saving and environmental benefits related to each retrofit action.

	Annual primary energy saving for operation (GJ/y)	Avoided annual GWP ($kgCO_{2eq}/y$)	Avoided annual ODP ($kgCFC_{11eq}/y$)	Avoided annual AP ($kgSO_{2eq}/y$)	Avoided annual EP ($kgPO_{4eq}^{3-}/y$)	Avoided annual POCP (kgC_2H_{4eq}/y)
Envelope insulation						
Walls	1.91	143.40	−4.5 E−06	0.11	0.02	0.46
Roof	0.16	26.00	−9.8 E−06	−0.11	−0.01	0.12
Ground floor	2.00	109.57	−1.0 E−03	0.15	0.03	0.58
PV plant	26.66	1807.65	1.8 E−04	7.44	1.66	0.71
Condensation boiler	1.29	35.71	−1 E−06	−0.08	−0.05	0.09
Total	32.02	2122.33	−8.6 E−04	7.51	1.65	1.96

3.5. Interpretation

3.5.1. LCIA results: a contribution analysis

Table 7 shows the results for the LCIA of the retrofit measures described above.

A contribution analysis was carried out to assess the role of each retrofit action in the LCIA indicators (Table 8).

If all the retrofit actions under assumption were implemented, the CED caused by them would amount to 274.3 GJ. The most significant contribution would be given by the envelope's thermal insulation, which affects CED for about 80%, while the share of the PV plant results about 18% (49 GJ). The production process of the high-efficiency boiler would affect the CED for about 2% (6.8 GJ).

The renovation of the building ground floor would cause the highest contribution to the CED. This was essentially due to the thermal mass of the employed materials. In fact it would require the dismantling of the existing ground floor and the reconstruction of another one with improved thermal properties. In detail, the renovation of the ground floor would generate the highest contribution in each of the estimated impact categories, except for POCP and EP that were mostly affected by the PV plant production. The impact of ground floor renovation accounted for about 43% on GWP, while the retrofit actions on the roof and the walls accounted for 8.87% and 20.16%, respectively. The PV plant contributed for 24% to GWP. Fig. 5 shows the contribution of each retrofit option to GWP.

POCP and EP were mostly due to the production of the PV cells, in particular due to the production of polycrystalline silicon wafers, which accounted for 70% in POCP and 63% in EP. The retrofit actions of the envelope contributed to EP and POCP for about 24%. With regard to AP, the ground floor renovation and the PV plant contributed for 28.6% and 27.7%, respectively. ODP is mostly due to the ground floor retrofit. With regard to the condensation boiler it contributed for about 13% to EP, about 5% to AP and POCP, while its contribution to ODP was negligible compared to the other retrofit actions. It accounted for 3.6% in GWP.

3.5.2. Energy and environmental benefits of the assessed retrofit actions

The environmental effects on the building life-cycle were assessed for the proposed retrofit actions. To this aim the energy and environmental impacts caused by the assumed retrofit actions (see Table 7) were compared with the saved primary energy and the avoided environmental impacts.

As shown in Table 9, all the energy and environmental indicators would undergo a net reduction, when implementing the retrofit actions. With regard to the environmental impacts they would be reduced by about 30–35%, depending on the indicators, except for ODP. The most significant contribution to such an impact was given by the renovation of the ground floor. It increased, essentially due to the production of the XPS (Extruded Polystyrene) layer to be used in the ground floor's retrofit. The PV plant resulted to be the most effective measure to save primary energy and to avoid impacts, contributing for nearly 80% in the majority of the assessed categories. Furthermore, it resulted in the unique actions which involve a reduction in ODP (21%).

Table 10
Primary energy consumption for the building end uses after retrofit.

End uses	Lifespan consumption (GJ)	Specific consumption (GJ/m^2y)	Retrofit saving (GJ)
Heating	85.4	0.02	448.1
Cooling	138.4	0.03	10.5
DHW	401.1	0.07	34.9
Cooking	133.4	0.02	0.0
Electric appliances	546.6	0.10	1431.4
Other uses	97.7	0.02	0.3
Total	1402.6	0.26	1925.2

Table 11
Energy Payback Time, Environmental Payback Time and Energy Return Ratio for the retrofit scenarios.

	$E_{P,T}$ (years)	$Em_{P,T}$ (years)	*ER*
Envelope insulation			
Walls	21.23	27.43	2.36
Roof	42.62	30.58	1.17
Ground floor	26.54	34.85	1.88
PV plant	1.71	1.34	29.17
Condensation boiler	4.74	3.81	10.55
Total	8.65	8.23	5.78

The roof insulation caused the lower contribution in the net energy saving, which resulted in 0.90 GJ/y. This was due to the already low thermal transmittance of the existing roof. Therefore the related life-cycle impacts were nearly equal to the related energy and environmental benefits.

Table 10 shows the primary energy reduction for each end-use calculated through TRNSYS simulations. The heating energy demand, which is related to the retrofit scenarios of the building envelope, decreased more than 80%. With regard to non-thermal uses, the PV plant allowed a primary energy saving of 72%. Such a saving was estimated taking into account the efficiency of the Italian Electricity Mix [36].

All the retrofit actions involved the reduction of the specific energy consumption for operation up to 260 MJ/(m^2 year). This outcome indicates that the retrofit shifts the building in the low-energy building category.

In order to get a deeper description of the energy performance of the retrofit actions and to compare different alternatives, the following payback indices were added to the EPD set: the Energy

Payback Time, the Emission Payback Time, and The Energy Return Ratio [14].

In detail, the Energy Payback Time ($E_{P,T}$) of a building retrofit action is the time needed to save as much energy (valued as primary) as that consumed during all the life cycle phases of each retrofit component/material/technology:

$$E_{P,T} = \frac{CED}{E_{s,y}} \tag{1}$$

where CED was calculated with regard to the life cycle of the retrofit action (GJ), and $E_{s,y}$ is the yearly saving of primary energy due to the retrofit action (GJ/year).

The Emission Payback Time (Em_{PT}) is the time during which the avoided emissions by the application of the retrofit actions are equal to those released during the life-cycle phases of each component. The authors decided to calculate the $Em_{P,T}$ with regard to the GWP index to express the environmental pollution [37–38]. Then it was defined as

$$Em_{PT,GWP} = \frac{GWP}{GWP_{s,y}} \tag{2}$$

where GWP was calculated with regard to the life-cycle of each retrofit action (kg $CO_{2\text{-eq}}$), and $GWP_{s,y}$ is the GWP avoided yearly after the retrofit (kg $CO_{2\text{-eq}}$/year). It depends on the previously assessed $E_{s,y}$ and on the reference emission factor of the electricity mix and national gas-fired heating plants.

The Energy Return Ratio (E_R) represents how many times energy saving exceeds global energy consumption:

$$E_R = \frac{E_S}{CED} \tag{3}$$

where E_S is the total saving of primary energy during the lifespan of each retrofit action (GJ).

Table 11 shows the results for the previous indices.

3.6. Discussion of the results

The assessment of the life cycle energy consumption of the examined building before and after retrofit actions implementation aims to highlight the relevance of the contribution provided by each retrofit measure to the embodied and operating energy balances in the whole building life-cycle.

The following main hot-spots can be highlighted from the study:

– The LCA of the existing building confirmed that generally the operation step involves the highest contribution to the life cycle primary energy consumption, accounting for 72% of the CED. The monitoring of the user behaviour during the operation step showed that the building annual operating energy mostly arises from the electricity consumption for lighting, electrical appliances and summer cooling, followed by the energy consumption for heating and DHW.
– The outcomes of the LCA of the building retrofit showed that these actions would cause additional primary energy consumption and environmental impacts mostly due to the production phase, but looking at the building eco-profile as whole, the CED results decreased: the operating energy was reduced; an extra embodied energy was involved for the production of the retrofit actions. The end-of-life on the building life-cycle increases due to the demolition energy of about 2%.
– Looking at the energy and GWP payback times, the energy and environmental benefits related to the retrofit scenarios would fully repay the life cycle impacts in a short period in comparison with the expected life-time of the retrofit actions themselves. Some of the retrofit actions on the envelope would involve high values for E_{PT} and E_{mPT}, because they provide the highest GER and the highest GWP values with the lowest energy saving and the lowest environmental benefit (avoided GWP). It is evident that the lowest payback times resulted for the PV plant, since it causes the most significant energy saving and environmental benefit in terms of avoided GWP. With regard to the Energy Return Ratio, under the implementation of all the actions, it will be equal to 6.

If all the proposed retrofit measures were implemented, the building CED would decrease from 855 MJ/m^2 year to 555 MJ/m^2 year, while GWP would decrease from 59 kgCO_{2eq}/m^2 year to 40 kgCO_{2eq}/m^2 year.

At the same time there would be an increase of the embodied energy of the building of nearly 27%, from 1217.4 GJ to 1547.5 GJ, associated to the production of the retrofit materials and components. The increase of demolition energy would be not higher than 3%.

Table 12 shows the variation of the building CED related to each retrofit action, also pointing out the contribution to the variation of embodied, operating and demolition energy.

In detail, the building operating energy would decrease from 3327 GJ to 1403 GJ (−58%), during the whole lifespan. Such a reduction is essentially due to the generation of electricity by the PV plant which induces a whole reduction of 1431 GJ, contributing 74% to the total reduction of the operating energy (Fig. 6).

Table 12
Contribution to the building CED from each retrofit action (GJ).

Retrofit action	Embodied energy	Operation energy	Demolition energy	CED
Before retrofit	1217.4	3327.0	100.6	4645
After retrofit	1547.5	1403.0	103.5	3054
Shell retrofit				
Wall	69.8	−165.0	0.3	−95.0
Roof	38.0	−45.5	1.1	−6.4
Ground floor	110.7	−210.9	1.3	−98.9
Plant retrofit				
PV plants	98.1	−1431.0	0.1	−1333.0
Condensation boiler	13.6	−71.6	0.1	−57.9
Total	330.10	−1924.0	2.9	−1591

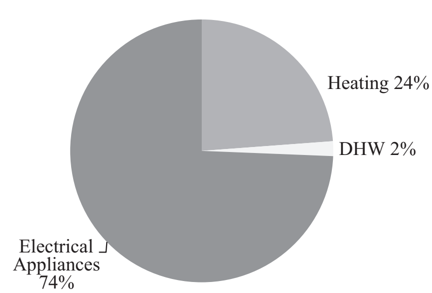


Fig. 6. Contribution of end-uses to the reduction of the building operating energy.

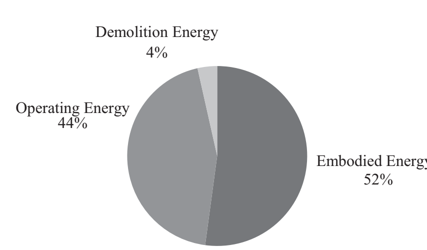


Fig. 7. Rates of embodied energy, operating energy and demolition energy in the building life-cycle after retrofit.

With regard to the building embodied energy, it would increase up to the 27% of the existing building's one. It is mostly due to the renovation of the ground floor (33%), and to the production of the PV plant (30%). The retrofit of the external wall affects for about 21%, while the roof retrofit affects for 11%, and the production of the condensation boiler for only 4%.

Fig. 7 clearly shows the change of the relative significance of the embodied energy and operating energy assuming the above studied retrofit scenarios. While the former one upgrades from 26% to 52%, the latter one decreases from 72% to 44%. The variation of demolition energy is not higher than 4%.

4. Conclusions

Energy and environmental performances of buildings strictly depend on many factors related to the climatic conditions of the construction site, the choice of construction materials for building envelope, plants and equipment, design, installation and use. Further the users' behaviour is a significant factor which heavily affects the energy consumption during operation.

By definition, an eco-building closely interacts with its environment. In such a building natural phenomena, such as natural ventilation, day lighting, passive cooling and heating, and renewable energy sources, are integrated in a thermal insulated envelope framework with energy efficient systems. Then interactions between building and climate, plants, and users have to be taken into account. This aspect is evident in new building's design process, but it is even more important in the design phase of an existing building renovation, during which energy saving actions are developed. Several studies on the design phase of buildings have been carried out, but few analyses have developed the energy and environmental implications of retrofit actions.

The literature review showed that the assessed existing building is representative of the standard Mediterranean single-family houses with regard to the primary energy consumption for end use and CO_{2eq} emissions starting from the results of a LCA study of a building; a set of energy retrofit actions was planned in order to improve building energy and environmental performances of the original building. Then a life-cycle approach was applied in order to undertake the related eco-profile. Thus, a balance between energy saving and environmental benefits and drawbacks concerning the assessed retrofit actions was carried out.

The most significant conclusion of the research is that the lower the operational energy the higher the embodied energy. In fact, the outcomes of the above case study highlight that whichever action is implemented, it determines an additional consumption of natural resources and environmental emissions in the pre-use and end-of-life steps, thereby increasing embodied energy and even influencing the demolition phase in terms of energy consumption and environmental impacts.

These findings pointed out the relevance of LCA in the assessment of the building energy and environmental performances. There is a strong interplay among all the phases of a building life-cycle, as each one can affect one or more of the others, highlighting the relevance of the life-cycle approach to perform a reliable and complete building energy and environmental assessment. Such an approach should be adopted in every country to carry out more reliable energy and environmental certification processes.

Obviously the outcomes of the above study derive from the specific conditions of the assessed building, with its features, the adopted construction techniques and materials, the behaviour of users, the site-specific climate, and the Italian energy mix. However, there is a remarkable result that can be generalized in other geographical contexts, that is the shifting significance of the life-cycle phases when retrofit actions are undertaken to improve the energy and environmental performance of a building.

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